NIR Luminosity Function of Galaxies in Close Major-Merger Pairs and Mass Dependence of Merger Rate

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ABSTRACT

A sample of close major-merger pairs (projected separation $5 \leq r \leq 20h^{-1}$ kpc, K_s band magnitude difference $\delta K_s \leq 1$ mag) is selected from the matched 2MASS-2dFGRS catalog of Cole et al. (2001). The pair primaries are brighter than $K_s = 12.5$ mag. After corrections for various biases, the comparison between counts in the paired galaxy sample and counts in the parent sample shows that for the local 'M$_*$ galaxies' sampled by flux limited surveys, the fraction of galaxies in the close major-merger pairs is 1.70±0.32%. Using 38 paired galaxies in the sample, a K_s band luminosity function (LF) is calculated. This is the first unbiased LF for a sample of objectively defined interacting/merging galaxies in the local universe, while all previously determined LFs of paired galaxies are biased by mistreating paired galaxies as singles. A stellar mass function (MF) is translated from the LF. Compared to the LF/MF of 2MASS galaxies, a differential pair fraction function is derived. The results suggest a trend in the sense that less massive galaxies may have lower chance to be involved in close major-merger pairs than more massive galaxies. The algorithm presented in this paper can be easily applied to much larger samples of 2MASS galaxies with redshifts in near future.

Subject headings: galaxies: evolution—-galaxies: starburst—-galaxies: luminosity function, mass function

1. Introduction

Galaxy-galaxy interactions/mergers are very important in the cosmic evolution of galaxies. In the hierarchical galaxy formation paradigm, galaxies and galactic structures are formed through merging of smaller galaxies/structures (Kauffmann et al. 1993; Cole et al. 2000). There is strong evidence that galaxy-galaxy interactions/mergers can significantly enhance the star formation rate (SFR) in galaxies involved (see Kennicutt 1998 for a review). There is also evidence that the strong evolution in the cosmic SFR is due to a population of peculiar/interacting starburst galaxies which are closely related to galaxy mergers (Brinchmann et al. 1998). Theoretical simulations (Barnes 1990) and observations (Schweizer 1978; Kormendy & Sanders 1992) show that gas-rich late-type galaxies transform to gas-poor early-type E/S0 galaxies through galaxy mergers. This process may also be responsible for the formation of bulges of disk galaxies. The AGN activity, another physical process linking the mass to the light, may also be closely related to galaxy-galaxy interactions/mergers if the central black holes in AGNs are built up mostly in galaxy mergers, given the tight correlation between the black hole mass and the bulge mass (Franceschini et al. 1999). During the merging, the tidal torque can send large amount of gas and stars deep into the galactic nuclear region, and therefore feed a pre-existing black hole very efficiently, leading to enhanced AGN activity. In summary, galaxy-galaxy interactions/mergers play a central role in four of the most important processes in galaxy evolution, including mass assembly, star formation, morphological transformation and AGN activity.

There are two classical methods to select interacting/merging galaxies. One is to identify binary galaxies. And the other is to find galaxies with peculiar morphology (e.g. with tidal tails, double nuclei, or distorted disc). The latter has the advantage of including both pre- and post-mergers, and the identifications need not to be confirmed by redshift

data. Studies based on this method found strong evolution in the fraction of major-mergers (galaxy pairs with mass ratio $\lesssim 3$), particularly for massive galaxies (Brinchmann et al. 1998; Le Févre et al. 2000; Conselice et al. 2003). However, these results may suffer uncertainties due to difficulties in quantifying the morphological peculiarity and in detecting the interaction signatures in high z galaxies because of poor spatial resolutions and the cosmic dimming. In contrast, it is easy to define binary galaxies quantitatively and objectively. This makes an objectively defined comparison between local merger events and high z merger events possible. However, earlier studies of pair fraction and its cosmic evolution have suffered seriously from the contamination of unphysical pairs because of the lack of redshifts or highly incomplete redshift data (Zepf & Koo 1989; Burkey et al 1994; Carlberg et al. 1994; Yee & Ellington 1995; Woods et al. 1995; Patton et al. 1997; Wu & Keel 1998). In two recent studies using samples of galaxies with measured redshifts, Le Févre et al (2000) and Patton et al. (2002) found $m = 2.7 \pm 0.6$ and $m = 2.3 \pm 0.7$, respectively, where m is the evolution index in the evolution function of the merger rate: $R_{mg} \propto (1 + z)^m$. In a series of papers, Patton et al. (1997; 2000; 2002) pointed out that in studies of merger rate and evolution, it is very important to correct various systematic biases, and results from comparisons between mismatched samples of low-z and high-z galaxies are not very meaningful.

The best way to constrain the merger rate and its cosmic evolution is to compare differential pair fraction functions at different redshifts. A differential pair fraction function (DPFF) is defined by ratios between number of paired galaxies and the total number of galaxies in luminosity (or stellar mass) bins. Such functions are not sensitive to sample selection (flux limited or volume limited) and therefore can be compared without bias between different studies. DPFF can be determined by comparing the luminosity (mass) function of paired galaxies with that of total galaxies. In this paper, we estimate the local K_s ($2.16\mu m$) band luminosity function of close major-merger pairs, and derive from it the

DPFF in the z=0 universe. The very close relation between the K_s band luminosity and the stellar mass means that for the first time we can have the mass function of the paired galaxies and the mass dependence of the merger rate. Since this can be compared directly to the predictions of the hierarchical galaxy formation simulations (e.g. Benson et al. 2002), it will provide an important test for these simulations. Through out this paper, we adopt the Λ-cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, $h = H_0/(100$ km sec^{-1}Mpc$^{-1})$.

2. Sample Selection

The parent sample is selected from the matched 2MASS-2dFGRS catalog of Cole et al. (2001), which has 45289 galaxies with measured J ($1.25\mu m$), H($1.65\mu m$) and K_s ($2.16\mu m$) magnitudes from the Extend Source Catalog (XSC) of 2MASS. The default K_{20} magnitude is used for the K_s band fluxes (Jarrett et al. 2000). Among 45289 galaxies, 17173 have measured redshifts from the 2dFGRS survey. It is known that the coverage of the 2dFGRS survey is not uniform, and there are holes between individual 2dF fields (Colless et al 2001). In order to minimize the uncertainties in our pair statistics due to the uneven redshift coverage, we restrict the parent sample to galaxies which have the redshift completeness index $c_z \geq 0.5$, where c_z is defined as the ratio between the number of galaxies with measured redshifts and the total number of galaxies within 1 deg radius from the center of the galaxy in question. Our final parent sample has 19053 galaxies, of which 14083 have measured redshifts (74% redshift completeness). The number counts of all galaxies and of galaxies with measured redshifts in the parent sample are plotted in Fig.1. Apparently the sample is complete down to $K_s = 13.5$, which is the completeness limit of the XSC (Jarrett et al. 2000). There is no significant dependence of the redshift completeness on the K_s magnitude.

In the pair selection procedure, we search for neighbors around every galaxy with

a measured redshift in the parent sample. Neighbors are not required to have measured redshifts. Among the matches, we select pairs according to the following criteria: (1) The K_s magnitude of the primary is not fainter than 12.5. A primary is defined as the brighter component of a pair. (2) At least one of the components has measured redshift. (3) When both components have measured redshifts, the velocity difference is not larger than 500 km sec^{-1}. (4) The projected separation is in the range of $5 \leq r \leq 20h^{-1}$ kpc. When only one component has measured redshift, the separation is calculated according to that redshift and the angular distance between the components. (5) The K_s difference between the two components is not larger than 1 magnitude. (6) Not in clusters. According to criteria (1) and (5), all selected galaxies in the pair sample are brighter than K_s=13.5, the completeness limit of the parent sample. This ensures the completeness of the pair sample. Criteria (4) and (5) restrict our pairs to "close major-merger pairs". This not only reduces the contamination of unphysical pairs among those with only one measured redshift, but also confines our sample to pairs which have high probability to merge within a few 10^8 years (Patton et al. 2000). Our final sample has 19 galaxy pairs (38 galaxies). Among them, 3 pairs have both components with measured redshifts, and 16 have only one component with measured redshift. The redshift range of the galaxy pairs is $0.016 < z < 0.070$ with a median of z=0.039.

3. Pair Fraction and K_s Band Luminosity Function

Two biases in our pair selection have to be corrected. First, pairs of both components without measured redshift are missed in our sample. Given the minimum fiber separation of the redshift survey ($\sim 30''$, Colless et al. 2001) and the median separation of our pairs ($21''$), it is very likely that the fraction of missing pairs is significantly higher than estimate from Poisson statistics (7%). An empirical approach is taken to estimate this fraction: in

the parent sample there are 350 pairs of galaxies with projected separation $< 30''$, of which 31.7% having both components without measured redshift. Secondly, the 16 single-redshift pairs are contaminated by unphysical pairs. In order to estimate how many false pairs are expected, Monte Carlo simulations reproducing the number counts and the redshift distribution of the parent sample are carried out. Coordinates in a 650 deg^2 sky region are randomly assigned to the simulated sources. A pair selection procedure, including all criteria listed in Section 2 except for (3), is applied to the simulated samples. A total of 100 such simulations are carried out. From this we found a mean of 6.36 with a standard dispersion of 2.62 for the total number of unphysical pairs. Since we miss 31.7% of all pairs, and one such false pair (with both components having measured redshift, not included in the pair sample) is already found in the real case, it is expected that $3.34 = 6.36 \times (1 - 0.317) - 1$ (with an error of $1.79 = 2.62 \times (1 - 0.317)$) unphysical pairs are among the 16 single-redshift pairs. Furthermore, the chance of being a false pair is proportional to the searching area, which is inversely proportional to z^2, multiplied by n which is the local density $(r \leq 10')$ of neighboring galaxies of $|\text{K}_\text{s} - \text{K}_\text{s}'| \leq 1$, with K_s' being the magnitude of the seed galaxy. This is reflected in the following 'false factor':

$$
Q_{false,i} = \begin{cases} 0 \pm 0 & \text{(pairs with 2 redshifts)} \\ (3.34 \pm 1.79) \times (n_i/z_i^2)/\sum_j(n_j/z_j^2) & \text{(pairs with 1 redshift)}, \end{cases} \tag{1}
$$

where the summation is over the 16 single-redshift pairs.

The pair fraction can be estimated as follows:

$$
f_p = \frac{A}{N_g} \times \sum_i^{N_{pg}}(1 - Q_{false,i}) \tag{2}
$$

where $N_g = 2079$ is the total number of galaxies in the parent sample brighter than $\text{K}_\text{s}=12.5$; $A = 1/(1 - 0.317)$ is the correction factor to compensate the incompleteness due to the missing pairs; $N_{pg} = 30$ is the total number of galaxies in the paired galaxy sample brighter than $\text{K}_\text{s}=12.5$. The estimated error of f_p is $err = \frac{A}{N_g} \times \sqrt{\sum_i^{N_{pg}}[(1 - Q_{false,i})^2 + e_{Q,i}^2]}$, where

e_Q is the error of Q_{false} as given in Eq(1). Note that the two galaxies in a pair have the same Q_{false} and e_Q. Using these formulae, we found a pair fraction of $f_p = 1.70 \pm 0.32\%$.

The K_s band luminosity function (LF) of paired galaxies is calculated using the V_{max} method (Schmidt 1968). Comparing the number counts of our parent sample with the 2MASS number counts of Kochanek et al. (2001) in Fig.1, we estimate that the effective sky coverage of the parent sample is 650 deg^2, with an error of $\sim 5\%$. We will ignore this error because it is much smaller than other errors. Given our pair selection criteria, both components of a pair have the same V_{max} determined by the K_s magnitude of the primary, the redshift of the pair, and $K_{lim} = 12.5$. The K_s band luminosity function and its error are calculated using the following formulae:

$$\phi(M_{K,i}) = \frac{A}{\delta(m)} \sum_{j}^{N_i} \frac{1 - Q_{false,j}}{V_{max,j}};$$ (3)

$$e_\phi(M_{K,i}) = \frac{A}{\delta(m)} \sqrt{\sum_{j}^{N_i} \frac{(1 - Q_{false,j})^2 + e_{Q,j}^2}{V_{max,j}^2}};$$ (4)

where $\phi(M_{K,i})$ is the luminosity function in the i-th bin of the K_s band absolute magnitude; N_i is the number of galaxies in that bin; $\delta(m) = 0.5$ is the bin width; $V_{max,j}$ is the maximum finding volume of the j-th galaxy in the bin. Other symbols have the same definitions as in Eq(2) and Eq(3). The results are listed in Table 1 and plotted in Fig.2. The parameters of the best-fit Schechter function of the LF are given in Table 2. It is well known that LF derived using V_{max} method can be affected by inhomogeneous spatial distribution of galaxies. In the redshift distribution of the 2MASS-2dFGRS matched catalog (Cole et al. 2001), there is evidence of clustering, particularly a dip around z=0.04 and a sharp peak around z=0.06. Therefore, the fluctuations of the LF of paired galaxies around the smooth Schechter function (e.g. the excess at $M_K = -22.75$) are possibly due to this effect.

The stellar masses, corresponding to the absolute magnitude bins of the LF, are also listed in Table 1. Following Kochanek et al. (2001) and Cole et al. (2001), we first translate

the isophotal K_s magnitude to the 'total' K_s magnitude ($\delta K_s = 0.2$ mag), then assume the conversion factor of $M_{star}/L_K = 1.32 M_\odot/L_\odot$ which is for a Salpeter IMF (Cole et al. 2001). The differential pair fraction function (Table 1 and Fig.2) is calculated using the Schechter functions of the paired galaxies and of 2MASS galaxies (Kochanek 2001) in the luminosity/mass range covered by the paired galaxy sample, with the error estimated from the quadratic sum of the error of the LF of paired galaxies and its deviation from the Schechter function. The last bin is not included because there is only a single galaxy in the bin and therefore the value is too uncertain. Although error bars are substantial, some general trends can be identified in Fig.2. Unlike the LF of 2MASS galaxies, the LF of paired galaxies has a negative slope in the faint end, suggesting that galaxies with low stellar mass are less likely to be involved in the close major-merger pairs. Indeed the DPFF shows a significant trend in the sense that in the low mass bins the pair fraction is low. This result appears to be in contradiction with the simple 'chance hypothesis', which states that if pairs are formed by single galaxies falling into each other's gravitational influence zone through random motion, then the fraction of major merger pairs among less massive galaxies should be relatively high because less massive galaxies are more abundant than more massive galaxies. The major reason for relatively low pair fractions in the low mass bins is perhaps the gravitational perturbations due to massive neighbors.

4. Comparison with Earlier Studies

Many authors have attempted to estimate the pair fraction in the local universe (Zepf et al. 1989; Burkey et al. 1994; Carlberg et al. 1994; Yee et al. 1994; Patton et al. 1997; Patton et al. 2000). Patton et al. (2000), using the SSRS2 sample of galaxies with redshifts, derived a pair fraction of 2.26±0.52% for close pairs. This is slightly higher than what is found in this work ($f_p = 1.70 \pm 0.32\%$). However, we have restricted our pair sample to

major-merger pairs ($\delta K_s \leq 1$, corresponding to a mass ratio of ≤ 2.5). In the pair sample of Patton et al. (2000), there is no restriction for the magnitude difference while an absolute magnitude range of $-21 < M_B < -18$ is imposed. Since missing secondaries is perhaps the most important source of incompleteness of a pair sample, we strongly argue that a maximum magnitude difference should be applied in any analysis on pair statistics. The restriction to major-merger pairs also makes the comparison to results of studies on peculiar galaxies easier because those galaxies are mostly major-mergers (Conselice et al. 2003).

Xu & Sulentic (1991), Rabaca & Sulentic (1994), Soares et al. (1995) and Hernandez Toledo et al. (1999) calculated the B band luminosity functions of paired galaxies. These results suggest a rather constant pair fraction of $\sim 4 - 10\%$. The most serious bias in these analyses is due to the mistreatment of paired galaxies as singles. Namely, the V_{max} of each paired galaxy is derived from its own B band magnitude, with the cutoff of $B_{lim} = 14.5$. In this case, the quantity $1/V_{max}$ is an *incorrect* estimator of the contribution of a paired galaxy to the density of the population. This is because the finding of one component of a pair depends on the finding of the other component of the same pair (otherwise neither of the two galaxies will be included in the paired galaxy sample), and the two components have different maximum finding volumes due to different luminosities. Therefore, contrary to the definition of V_{max}, the component with the larger $V_{max,1}$ may not be found in such a volume because the other component (with a smaller $V_{max,2}$) will be missing beyond $V_{max,2} < V_{max,1}$. Keel & Wu (1995) derived a LF for galaxy mergers selected morphologically. The weakness of that work is a rather heterogeneous and arbitrary sample selection.

In summary, the K_s band luminosity function of galaxies in close major-merger pairs presented in this paper is the first unbiased luminosity function of a sample of objectively defined interacting/merging galaxies in the local universe. The algorithm presented in this

paper can be easily applied to much larger samples of 2MASS galaxies with redshifts in near future when the SDSS redshift survey data and the 6dF survey data are fully released. The local mass function of paired galaxies will be compared with those of the high-z galaxies when deep SIRTF survey data in the MIR bands are available. The rest frame K_s band radiation of galaxies of z=0.6 and z=1 will be detected in the SIRTF-IRAC $3.6\mu m$ band and $4.5\mu m$ band, respectively. Extensive redshift surveys for these galaxies have been planned (Lonsdale et al. 2003). Comparisons between mass functions of paired galaxies in the $z = 0$, 0.6 and 1 universe will reveal the evolution of merger rate and its mass dependence, and provide strong constraints to theories of galaxy formation and evolution.

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Table 1. K_s Band Luminoisty Function of Paired Galaxies and Differential Pair Fraction

(1)	(2)	(3)	(4)	(5)	(6)	(7)
$M_K - 5\log(h)$	$\log(M_{stars}/h^{-2})$	$\log(\phi/h^3)$	error	N	pair fraction	error
(mag)	$(M_\odot)$	$(Mpc^{-3}mag^{-1})$			(%)	
-21.75	10.24	-4.25	-4.35	2	0.78	0.50
-22.25	10.44	-4.07	-4.31	4	1.27	0.65
-22.75	10.64	-3.76	-4.20	9	1.89	1.25
-23.25	10.84	-3.94	-4.42	11	2.45	0.84
-23.75	11.04	-4.38	-4.74	6	2.54	1.17
-24.25	11.24	-4.64	-4.99	5	1.85	0.97
-24.75	11.44	-5.60	-5.60	1		

Table 2. Paremeters of Schechter Function of K_s LF of Paired Galaxies

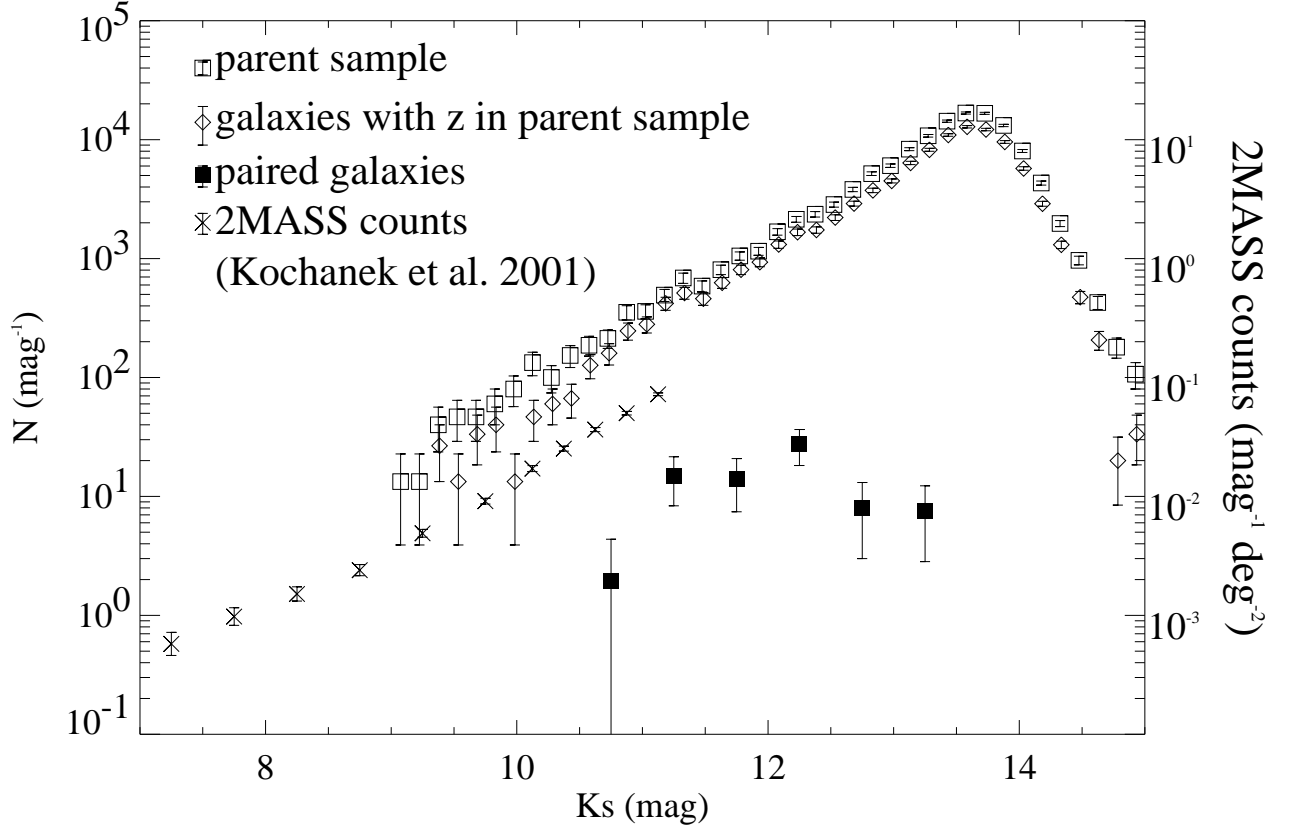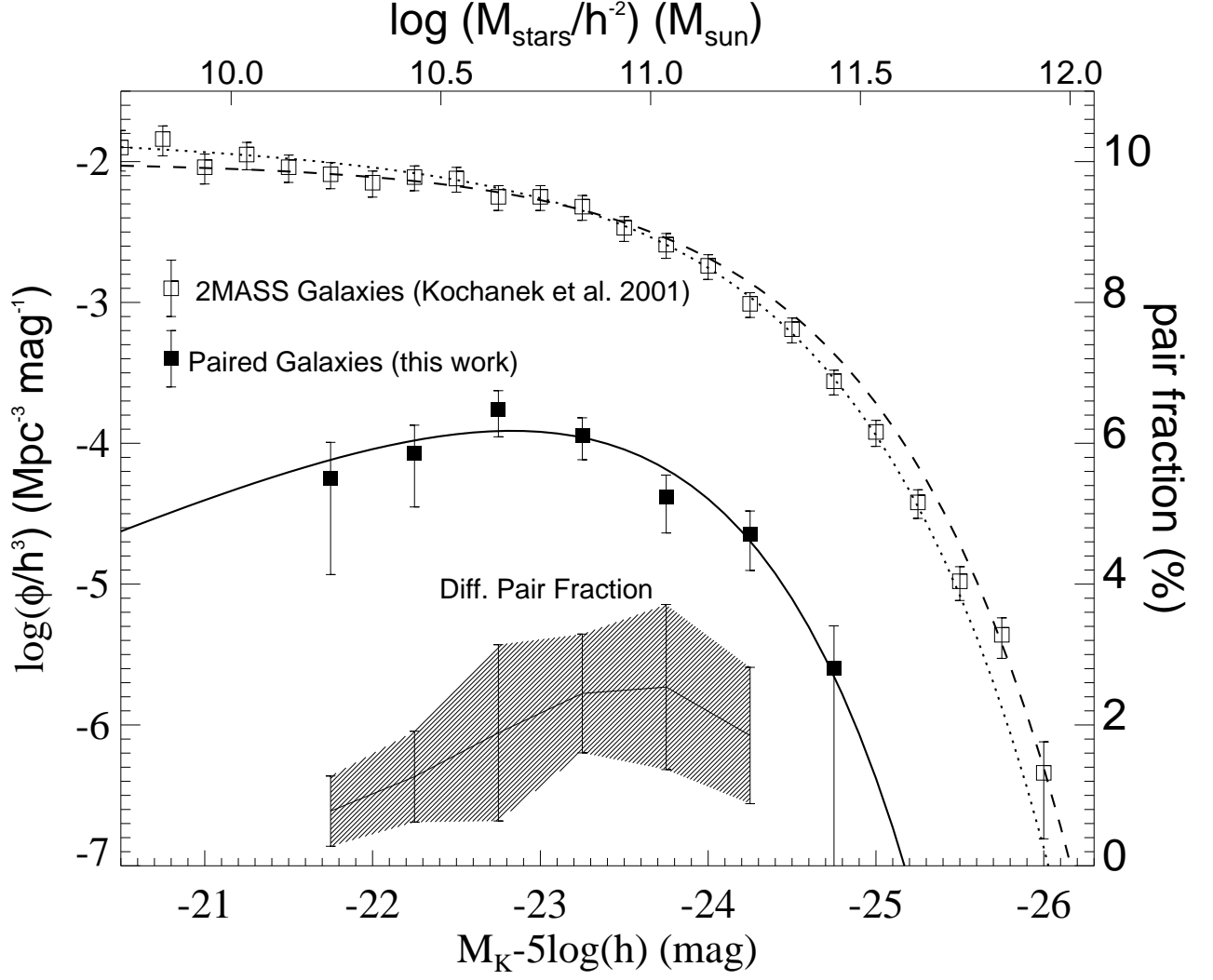| α	error	$M_* - 5\log(h)$	error	$\log(\phi_0/h^3)$	error
0.30	0.56	-22.55	0.25	-3.46	0.13

Fig. 1.— K_s band number counts.

Fig. 2.— K_s band luminosity functions and stellar mass functions, and differential pair fraction (right coordinates). The lines are Schechter functions of the LF of paired galaxies (solid), of the LF of 2MASS galaxies by Kochanek et al. (2001) (dotted), and of the LF of 2MASS galaxies by Cole et al. (2001) (dashed). The shaded area presents the differential pair fractions and the errors.